TETHERED SATELLITE SYSTEM INTERACTIONS WITH THE IONOSPHERIC PLASMA

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ABSTRACT

The Tethered Satellite System (TSS) program was designed to provide the opportunity to explore certain space plasma-electrodynamic processes (associated with high-voltage bodies and electrical currents in space) and the orbital mechanics of a gravity-gradient stabilized system of two satellites linked by a long conducting tether. A unique data set was obtained during the TSS-1R mission in which the tether emf and current reached values in excess of 3500 volts and 1 amp, respectively. The insight this has allowed into the current collection process and the physics of high-voltage plasma sheaths is significant. Previous theoretical models of current collection were electrostatic—assuming that the orbital motion of the system, which is highly subsonic with respect to electron thermal motion, was unimportant. Moreover, these models did not include the effects of ionization. These assumptions may still be acceptable for the case of relatively slow-moving sounding rockets. However, the TSS-1R results show that motion relative to the plasma—and especially ionization of neutral gases—do affect current collection and must be accounted for in orbiting systems. The same processes are also of critical importance to a proper characterization of the plasma environments of large structures in space such as the International Space Station.

Background

The Tethered Satellite System program was a binational collaboration between NASA and the Italian space agency (ASI) with NASA providing the Shuttle-based deployer and tether and ASI providing a satellite especially designed for tethered deployment. The TSS-1R mission, which was the second flight of the TSS hardware, was launched February 22, 1996 on STS-75 into a 300 km, circular orbit at 28.5 degrees inclination. Satellite flyaway occurred at MET 3/00:27 and a unique data set was obtained over the next five hours as the tether was deployed to a length of 19,695 meters. More complete treatments of the results discussed below are provided by papers in a *Geophysical Research Letters* special section on TSS-1R (Stone and Bonifazi, 1998).

Instrumentation and Measurements

Electrodynamic tethers convert mechanical energy into electrical energy in a classical demonstration of Faraday's law. The TSS-1R configuration was such that the satellite received a positive bias from the motional emf of the tether and collected electrons from the ionosphere. The resulting electrical current was conducted through the tether to the Orbiter where the circuit was closed back to the ionosphere (see Figure 1). There were four possible electrical configurations of the TSS: (1) open circuit with no current flow—which placed the full tether-generated emf across the open switch; (2) passive current closure—in which current was controlled by adding a load resistance in series with the tether and closure was through the collection of positive ions by conducting surfaces on the negatively charged Orbiter; (3) addition of the SETS experiment's FPEG (electron gun) to the above circuit to discharge the Orbiter; and (4) use of the ASI-provided Core electron gun—in which case tether current flowed directly to the gun cathode (the Orbiter was not part of the electrical circuit) and was emitted back in to the ionosphere. An electrical schematic is shown in Figure 2.

TSS-1R was instrumented to diagnose the environmental space plasma properties under highly non-equilibrium conditions. Mounting arrangements for the required ensemble of instruments are shown in Figure 1. Detailed descriptions of the instrumentation, which also flew on the TSS-1 mission, are provided in a special TSS-1 issue of *Il Nuovo Cimento* (1994).

Scientific and Technological Results

The most fundamental scientific result from the mission to date is the discovery that the various theoretical current collection models developed over the past seventy years (e.g., Langmuir-Blodgett, 1923, 1924; Beard-Johnson, 1961; Parker-Murphy, 1967; and Laframboise and Sonmer, 1993) do not include the full range of processes by which an electrically biased, mesosonic satellite (supersonic with respect to the ion sound speed but subsonic with respect to that of the electrons) interacts with its environmental space plasma. The predicted relation between the satellite potential and charge collection (the current-voltage characteristic) is, correspondingly, incorrect.

Current Collection in Space Plasmas

It became immediately obvious during the mission that serious differences existed between the current collection predictions of theoretical models and the measured results. For example Figure 3 shows that the attractive potential on the satellite required to collect a given current is typically an order of magnitude less than that predicted by models that account for the geomagnetic field but not orbital speed (e.g., the Parker-Murphy model). This shows that current collection is far more efficient than predicted and suggests that (1) the orbital velocity has a significant effect and (2) the requirement for rather rigid adherence of electrons to magnetic field lines assumed in the magnetically limited models may be too severe—at least in the near vicinity of the satellite (Papadapolous et al., 1998). New models are being developed which account for the above factors (Ma and Schunk, 1998; Singh, and Leung, 1998).

Plasma Sheath Physics

A sharp transition was observed in the particle and field environment when the satellite potential exceeded + 5 volts. This seems to suggest an abrupt modification of the physical processes operating in the satellite’s near vicinity (Winningham et al., 1998). Below + 5 volts, mostly accelerated ionospheric thermal electrons were observed. However, when the satellite potential exceeded the + 5 volt level, a sudden on-set of suprathermal (~ 200 eV) electrons, plasma waves, magnetic perturbations, and turbulence in the satellite sheath were observed (Winningham et al., 1998; Iess et al., 1998; Mariani et al., 1998; and Wright et al., 1998). The suprathermal flux intensity grew rapidly with increasing satellite potential and quickly swamped the ionospheric thermals. Specifically, as shown in Figure 4, a 10 V increase in satellite potential resulted in four orders of magnitude increase in the suprathermal electron flux (Winningham et al. 1998). It now appears that the conducting thermal control coating of the satellite may be the source of a large photo and/or secondary electron flux. However, their suprathermal energy remains a mystery.

Relatively energetic ions were observed flowing out of the satellite's sheath (Wright et al., 1998). The ram energy of ionospheric atomic oxygen ions is approximately 5 eV, so that the critical voltage for the transition discussed above is the level at which oxygen ions would be reflected or strongly deflected out of the sheath. It is suggested that the out-flowing ions, or possibly the expulsion of ions from the plasma sheath, may provide the free energy required to generate waves and drive the energization of the suprathermal electrons in the satellite's environment (Iess et al., 1998; Winningham et al, 1998; Papadopoulos et al., 1998). The azimuthal variation of out-flowing ion flux and the correlation between its intensity and plasma noise in the satellite's sheath are shown in Figure 5.

The Tether Break Event

The tether break, in retrospect, has provided an intriguing and potentially valuable event in which large currents (in excess of one amp) at high satellite potentials (greater than 1 kV) began flowing approximately 10 s prior to the break and continued for about 90 s *after* separation (Gilchrist et al., 1998). At MET 3/05:11, during a day pass, the tether suddenly broke near the top of the deployer boom. The break resulted from a flaw in the insulation surrounding the tether's conducting core. This allowed the ignition of a strong electrical discharge which melted the tether. At the time of the break, the satellite was deployed 19.7 km above the Orbiter and the motional emf generated by the tether was 3500 volts. The discharge, in effect, shorted the tether to the Orbiter's electrical ground. This minimized resistance in the system, drove the Orbiter to high negative potentials, and maximized both current flow in the tether (greater than one ampere) and the voltage imposed on the satellite (approximately 1 kV positive). Finally, and most intriguing, the tether current and satellite potential remained virtually unchanged as the tether broke and separated from the Orbiter. This event raises three fundamental questions: (1) How could currents greater than one ampere be collected by the satellite at the given voltages? (2) How were such large currents dissipated by the Orbiter prior to the break? and (3), How were these currents dissipated at the end of the broken tether after separation from the Orbiter?

It is apparent from Figure 6, that the current collected by the satellite during the break event, even taking into account its high potential, is much greater than would is predicated by the Parker-Murphy model. If the greatest latitude possible in the range of ionospheric thermal current is used, these results appear to be consistent with the range of I-V characteristics established under normal TSS operations—in particular, during the active part of the IV24 cycle just prior to the break event. If this is correct, then the I-V characteristic is not in agreement with theory, but is, at least, consistent with other, nominal operations of the TSS and, therefore, does not require different or additional physical mechanisms.

The ability of the Orbiter to dissipate the large tether current just prior to the break is surprising, in spite of its 600 volt negative bias. Collection of ionospheric atomic oxygen ions to neutralize the negative charge collected on the Orbiter is not feasible because of the low mobility of the relatively massive ions and the small area of the Orbiter's conducting surfaces.

On the other hand, emission of electrons would require an extremely efficient secondary emitter or the presence of a high density gas cloud—such as would be created by thruster operations. However, according to the Orbiter data, no thrusters or other gas or water releases were in progress at that time. Unfortunately, the TSS data set may not be sufficient to resolve this question.

The ability of the broken end of the tether to dissipate such a large current has been shown to depend on the ionization of gas contained in the tether core (see Figure 7) and or the evaporation of tether material by the discharge to form an ionizable vapor (Gilchrist et al., 1998).

Additional Investigations

(1) The characteristics of a high voltage, negatively charged spacecraft and its effects on the ionospheric plasma were investigated (Gentile et al. 1998; Aguero et al., 1998). This study—made possible for the first time by TSS-1R—is important because this it can lead to improved techniques for handling spacecraft charging effects, and for biasing antennas in space to enhance their coupling to the magnetospheric plasma. This may have direct applications to the measurement of dc electric fields in space.

(2) Magnetic field perturbations were observed in the vicinity of the satellite, when it was highly biased, which suggest the existence of a toroidal current system located approximately one radius from the surface (Mariani et al., 1998). This is in agreement with the predictions of a numerical model by Singh and Leung (1998), and is suggestive of E x B driven current systems in the magnetosphere. It could create a significant undesirable EMI and charged particle environment for certain types of measurements and experimental activities.

(3) Particle measurements strongly suggest the presence of pick-up ions in the satellite's near environment. This processes can greatly affect the structure of the satellite's sheath and its overall interaction with its space plasma environment.

(4) Satellite-ionospheric interactions can be studied under controlled conditions unique to the TSS-1R data set. These investigations may improve our understanding of the collisionless expansion of plasma into the void region of the satellite's wake (Samir et al., 1993; Stone et al., 1988). This process will directly affect the depth of the plasma depletion in the wake region and its effect on return currents to large structures in space.

Implications for Technological Applications

Figure 8 is a plot of the satellite potential required to collect a given current as a function of tether current. Note that the potential requirements of the Parker-Murphy model far exceed the actual TSS-1R data. This means that electron collection required much less work than predicted; and this, in tern, means that less of the available emf is used to collect the tether current—leaving more usable power. Considering only on the collection process at the satellite, usable power is defined by:

$$P_{usable} = I_{tether} (\Phi_{emf} - \Phi_{sat}).$$

(Note that in terms of the whole system, resistive potential drop in the tether and work done by the electron gun at the Orbiter to inject electrons back into the ionosphere must also be taken into account.)

Plotting usable power as a function of tether current in Figure 9 shows that the Parker-Murphy model predicts the usable power to increase with current to a peak at about 250 mA and then decrease to zero at about 440 mA. This is because the model predicts the collection process to become increasingly inefficient with increasing current so that eventually, all available energy is used to collect electrons and none is left to do useful work. Note, however, that this is not what actually happened. The importance of the enhanced current collection discussed earlier is apparent here because, due to the ease with which electrons are extracted from the ionosphere, the usable power developed by the TSS did not peak, but continued to increase over the range of the measurements (Papadopoulos et al., 1998).

Conclusions

It is apparent from the TSS-1R data set that (1) a sharp transition in the physics of the interaction between the TSS and the ionosphere occurs, when the satellite potential exceeds + 5 volts, in which electron flux to the satellite changes from being primarily accelerated ionospheric thermals, to being dominated by suprathermal electrons; and (2) the current-voltage characteristic, possibly as a result of the above transition, is in disagreement with the magnetically limited models (e.g., Parker-Murphy—which requires an order-of-magnitude higher satellite potential to collect a given current). The effects observed at the TSS satellite are shown schematically in Figure 10.

Current extraction from the ionosphere was surprisingly efficient—to the extent, in fact, that the TSS never pushed the ionospheric plasma's limits of conductivity. These results are extremely encouraging for scientific and technological applications of electrodynamic tethers, such as the generation and study of current systems, electromagnetic waves, or plasma disturbances in the ionosphere, the generation of electrical power or electrodynamic thrust, and the use of tethers as VLF/ULF antennas.

The above observations are also of critical importance because they would appear to define the plasma environments of large-scale structures in space. Note that the motional emf created by any conducting element moving through the geomagnetic field at orbital speed is in the range of 0.2 volts/meter. Therefore, spacecraft the size of the space shuttle Orbiter have an emf on the order of several volts, while the much larger International Space Station could have a much higher emf in the range of 10 to 20 volts. As seen above, this is sufficient to excite the transition in physical processes that appear to control the characteristics of the environmental plasma. The net effect is to greatly enhance electrical conductivity in the local plasma—thereby increasing the electrical current to charged surfaces for any given value of the spacecraft potential.

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FIGURE CAPTIONS

Fig. 1. Functional schematic of the TSS-1R instrumentation and hardware.

Fig. 2. Electrical schematic of the TSS-1R circuit.

Fig. 3. TSS-1R current-voltage characteristics compared to the characteristic predicted by the Parker-Murphy theory. Data was obtained from 6 Core electron gun controlled sweeps in the third IV24 operations cycle at a deployed distance of approximately 18 km. [after Stone and Bonifazi, 1998]

Fig. 4. Growth of the suprathermal electron flux density as a function of satellite potential [after Stone and Raitt, 1998].

Fig. 5. Azimuthal distribution of out-flowing ion flux density and the corresponding plasma noise level for satellite potentials of (a) 8 volts, and (b) 200 volts [after Stone and Raitt, 1998].

Fig. 6. Tether I-V characteristics during the tether break event.

Fig. 7. Schematic of the tether design showing the insulating core surrounded by an air-tight insulating sleeve.

Fig. 8. Voltage-current characteristic obtained from TSS-1R data compared with characteristics predicted by the Parker-Murphy model. [after Papadopoulos and Drobot, 1998]

Fig. 9. Usable power available from TSS-1R compared to the usable power predicted by the Parker-Murphy model. [after Papadopoulos and Drobot, 1998]

Fig. 10. A composite schematic of the complex array of physical effects and characteristics observed in the near environment of the TSS-1R satellite. [after Stone and Bonifazi, 1998]